INITIALIZATION AND OPERATION OF MERCURY, A 6-MV MIVA*

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Abstract

Mercury became operational in a stepwise manner to test the machine components after modifications[1] and reassembly at NRL. To avoid damaging the MIVA, extensive testing of the laser and PFL output switches was performed using dummy loads. Finally, the PFLs were connected to the MIVA and Mercury was fired into a simple cylindrical diode load with a Marx charge voltage up to 75 kV. Measured MIVA currents and voltages compare well with a circuit model of the MIVA fed by the measured PFL outputs and with PIC simulations of the MIVA and the diode load.

I. Description of Mercury

Mercury is a magnetically-insulated inductive voltage adder (MIVA) designed to produce 50-ns pulses with load voltages up to 6 MV at a current of 360 kA and deliver 100 kJ to a vacuum diode load.[2] The MIVA is formed by six induction cells that add the inputs from 12 pulse-forming lines (PFLs). Each PFL delivers a 50-ns pulse with a peak voltage of about 1 MV and a current of about 180 kA. Each cell adds the currents of two PFLs, connected at the top and bottom of the cell by "elbows", oil-filled coaxial lines with a 90° bend. Each cell contains azimuthal transmission lines that ensure symmetric power feed. Highly inductive cores within each cell allow the cells to be connected in series to sum their voltages and obtain 6 MV at the output. The cells have a 15″ ID evacuated central bore hole through which a center conductor is inserted. The center conductor is grounded at one end so that the output voltage appears at the other end. The polarity of the machine can be reversed by inserting the center conductor from the opposite end. The high voltage causes electrons to be emitted from the center conductor in negative polarity (or the outer conductor in positive polarity). In either polarity, the high current generates a magnetic field that is strong enough to prevent electrons from crossing between inner and outer conductors and so the adder is magnetically insulated.

II. Marx and Intermediate Stores

The Marx is a "Sandia-style" design with 36, 2.2-μF capacitors, which are rated for 100 kV. The Marx charges four intermediate-store (IS) capacitor bottles that are 4' long with a 4' OD with a capacitance of 9.5 nF each. A series output resistor between the Marx and the IS limits the Marx current below the 150 kA rating of the Marx switches. Each IS bottle has a laser-triggered gas-filled switch that connects to three of the PFLs. Once the four IS bottles are fully charged, a pulsed KrF laser beam is split into four beams that are focused inside each of the laser switches to trigger them. A diagram of Mercury that shows the layout of the machine tank components is shown in Fig. 1.

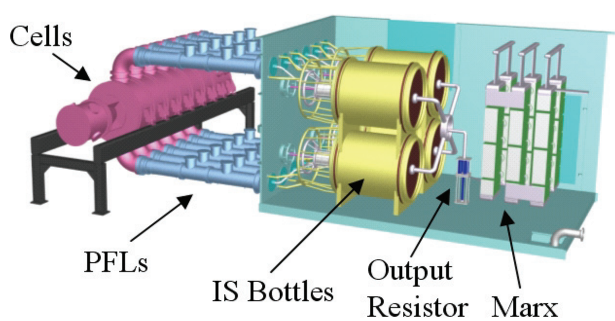

Figure 1. Diagram of the Mercury with cut-away view of the machine tank.

A stepwise procedure was followed to test the Marx, IS, and ancillary components, as well as calibrate electrical diagnostics. This procedure also allowed construction and validation of a detailed circuit model of the Marx-IS system.

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14. ABSTRACT
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A. IS Voltage Diagnostic Calibration

The IS bottle voltage monitors were calibrated with a 2-μF external capacitor charged to 25 kV. When switched into the IS bottle, the IS voltage oscillates with a peak of about 50 kV and a decaying peak envelope due to resistive losses. The calibration was done using Eq. (1), where V_{p0} is the peak of the ringing IS voltage envelope extrapolated back to the initial switch time, V_0 is the initial voltage on the external capacitance, C_1, and C_2 is the capacitance of the IS bottle, which is small compared to C_1 so that $V_{p0} \approx 2\,V_0$.

$$V_{p0} = V_0 \frac{2C_1}{C_1 + C_2} \qquad (1)$$

For the circuit model, the shunt resistance of the water in the IS bottles was determined by measuring the resistivity of water and using the relationship of Eq. (2), where R is the shunt resistance, ε is the permittivity of the water, ρ is the resistivity of the water and C is the capacitance of the IS bottle.

$$RC = \varepsilon\rho \qquad (2)$$

B. Marx Shots into a Short Circuit

The first shots on the Mercury Marx bank were into a short circuit load with a 30-kV charge. The last Marx capacitor was connected directly to the floor of the tank using braided cable. With the known charge voltage and RLC fitting of the measured Marx current, the inductance, series resistance, and current probe calibration factor of the Marx were determined. The measured capacitance, stamped on each Marx capacitor, was used to determine the equivalent series Marx capacitance of 63.2 nF. The Marx charge voltage monitors were calibrated at 10 kV by connecting a high voltage probe to the charging rails. Note that 30 kV was the lowest possible Marx charge voltage because the switch air pressure of 5 PSIG required at that level was just enough to ensure that oil did not leak into the switch envelopes. This voltage was low enough, however, to keep the Marx switch currents below rated values, even into a short circuit.

C. Marx Shots into an Open Circuit

The second series of shots with the Mercury Marx bank were with a nearly open-circuit load and a 30-kV charge. The output of the Marx was connected to a 5.42 kΩ resistive voltage divider and a self-breaking oil diverter switch. The diverter breakdown gap was adjusted to close after about 6 μs. The Marx shunt resistance, the calibration factor of the voltage monitor, the resistance of the diverter series resistor, and the calibration factor of the diverter current monitor were all determined with these shots.

D. Marx Shots into IS without Laser Switch Out

In the next series of shots, the Marx was connected to the IS bottles through the output resistor and fired at 30-kV charge without triggering the laser-triggered switches (LTSs). Also, the LTSs were filled with higher than normal pressures of SF_6 to ensure that they would not self break. The diverter was set to a small gap but did not close until after about four periods of oscillation between the Marx and IS (~10 μs). The inductance between the Marx and the IS was determined from these shots. Also, the IS voltage monitor calibrations and capacitances were verified. At this point, the circuit model of the Marx-IS system, shown in Fig. 2, was complete and agreed well with measured Marx current and IS voltages.

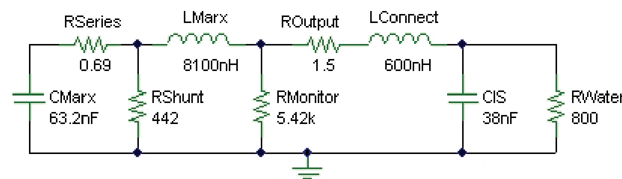

Figure 2. Simplified circuit diagram of the Mercury machine tank.

E. IS Dummy Load Shots

The next step was to raise the Marx charge voltage until the desired 3 MV on the IS bottles was reached while testing the LTSs. To avoid damaging the MIVA due to poor LTS timing, dummy loads were installed between the output of the LTSs and ground. The dummy loads were fabricated from Tygon tubing with a 1.75″ ID that was filled with $CuSO_4$ solution with a length of 20″ between metal end plugs. Three of these liquid resistors were attached in parallel between grading rings at the output of the LTS and ground as shown in Fig. 3. The ideal resistance between each bottle and ground would be about 14 Ω to critically damp the IS voltage and minimize the breakdown risk, however, only 27 Ω could be obtained with a saturated solution. However, modeling showed that the difference in effective pulse width was acceptably small. The desired peak IS voltage of 3.0 MV was obtained with a 75-kV Marx charge voltage. To be cautious, the Marx charge voltage was not raised further.

Figure 3. Photo of the IS dummy loads installed between a LTS (left) and ground (right).

III. PFL Dummy Load Shots

Concerns that excessive switch jitter would damage the MIVA led to installing dummy loads at the outputs of all 12 PFLs. These dummy loads were made using the “elbows” that normally connect the PFLs to the cells. The cells were moved away and the upper elbows were rotated upward so they could be filled with solution. The center conductor was removed and replaced with a 5″ long, 6″ OD stainless steel electrode with rounded edges. Using field plotting software, a capacitance of 0.66 nF was determined for the dummy load, which meant from Eq. (2) that a liquid resistivity of 6.3 Ω-m was required to match the 6.78-Ω PFL output lines. This was achieved with a 3.3 gram/liter solution of $CuSO_4{*}5H_2O$. Temporary wooden scaffolding was erected to hold the elbows in place. A picture of the PFLs with the dummy loads attached is shown in Fig. 4. Over 100 shots were taken with different combinations of Marx charge voltage and PFL output switch gap to obtain good statistics on the switch jitter[3] and determine the dependence on switch gap. Also, the degradation in output switch jitter with shot count was investigated and found to be minimal. Voltage and current monitors on the PFLs, calibrated earlier using resistive dividers and a cable pulser, gave signals that agreed with a circuit model that included the PFLs.

Figure 4. Photo of Mercury front end with PFL dummy loads that shows the inverted upper PFL elbows.

IV. Shots with Simple Cylindrical Diode

After determining that the total jitter in the PFL outputs was acceptable[3], all dummy loads were removed and the PFLs were connected to the inductive-adder cells. For our first shots into vacuum it was desired to field a load that was as benign as possible; having fixed impedance, leaving no debris in the system, and being reusable without breaking vacuum. A simple cylindrical diode achieved these goals. The cathode was just a hollow extension of the center conductor with a thin, “blade”, edge. The anode was just a flat plate termination of the 15″ outer conductor constructed of ½″ of carbon, to prevent ion emission and pinching, followed by ¾″ of aluminum with a fingerstock current contact to the outer conductor. The anode was designed to slide inside the outer conductor so that the diode AK gap could be adjusted from 0 to 12 cm. Because the final load chamber diameter was much larger than 15″, false work was installed to extend the 15″ outer conductor into the load chamber and allow optical access. An extension section was added between cell #6 and the load chamber to avoid debris problems and to ease analysis of measured MIVA currents. A diagram of the front end from cell #6 to the diode load is shown in Fig. 6.

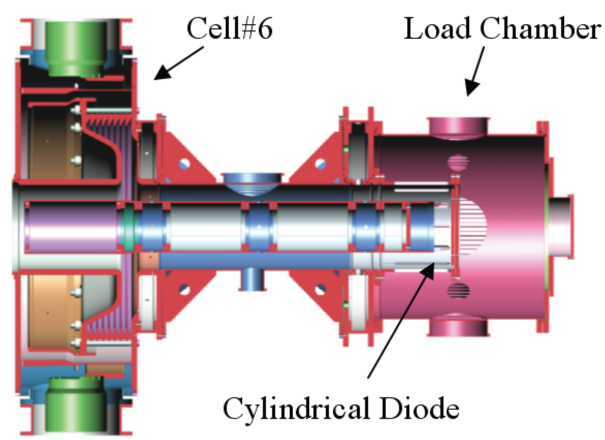

Figure 5. Diagram of Mercury front end from cell #6 to cylindrical diode load inside load chamber.

A series of shots were taken with first a 50-kV and then a 75-kV Marx charge with various diode AK gap spacings. Measured load impedances (defined as load voltage/anode current) compared well to PIC simulations of the diode as shown in Fig. 7 for the 75-kV case. Note that since direct voltage measurements were not possible due to the electron flow, the load voltage was determined using measured inner and outer conductor currents (either at just after cell #6 or just before the diode) and an equation from Mendel[4].

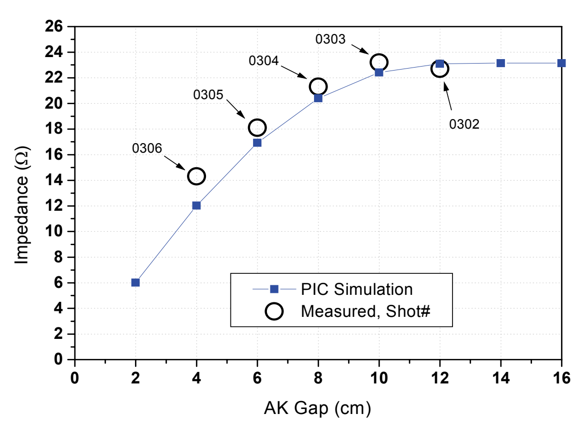

Figure 6. Comparison of measured and simulated load impedance vs. AK gap spacing at 75 kV Marx charge.

Detailed circuit modeling was done to verify that the MIVA and diode were behaving as expected. One circuit model used all 12 measured PFL outputs as input and included the time-varying impedance of the vacuum sections, which the model handles best with large diode AK gaps so that the diode runs in the self-limited state and there is little reflected energy. A more versatile circuit model for the MIVA is being developed.[5] The outer conductor currents agreed with the model at both cell #6 (Fig. 7) and the load (Fig. 8). While the inner conductor currents agreed at cell #6, the measured inner conductor current was lower than that of the simulation at the load location for a 75-kV Marx charge and 12-cm AK gap. However, the Mendel voltages at both locations are still in reasonable agreement with the model as shown in Fig. 10.

The 6 MV and 285 kA peak output of shot #0302 was achieved with a Marx charge of 75 kV and PFL output switch gaps of 4 cm giving a main pulse energy of about 75 kJ. This output level meets the requirements of currently planned radiography experiments. It is expected that the full rated output of 360 kA at 6 MV and 100 kJ could be reached, if later desired, by increasing the Marx charge voltage to 80 kV and widening the PFL output switch gaps to about 6 cm.

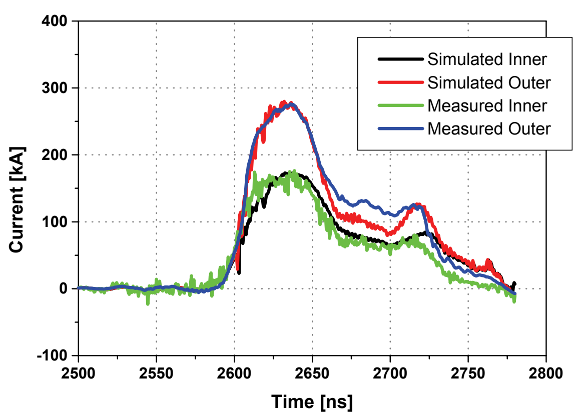

Figure 7. Measured and simulated currents at the cell #6 location on shot #0302.

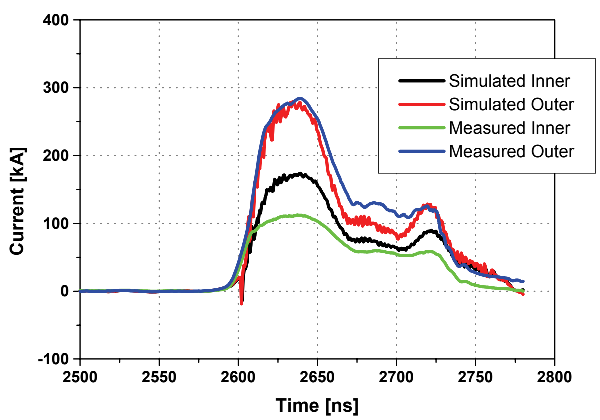

Figure 8. Measured and simulated currents at the load location on shot #0302.

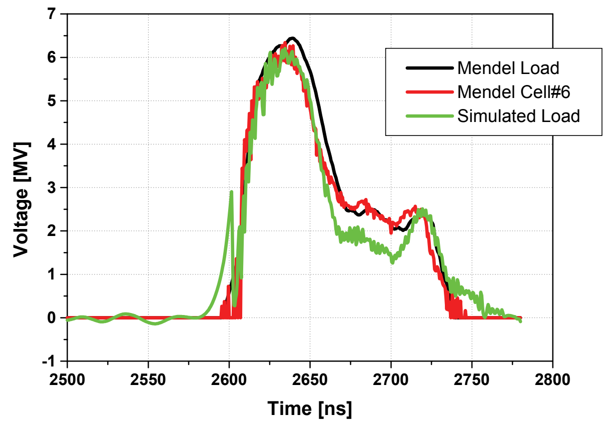

Figure 9. Mendel and simulated voltages shot #0302

In a final series of experiments with this diode, the carbon anode plate was replaced with 20 to 40 mils of tantalum foil to generate bremsstrahlung radiation and the AK gap set to 12 cm. About 500 Rad (CaF_2) at 1 meter were measured on the end plate of the load chamber in this mode. Measured doses agreed well with detailed PIC simulations that calculated x-ray output.[6]

V. SUMMARY

Detailed calibration, testing and simulation were performed including the use of dummy loads to test IS laser and PFL water switches. With a simple cylindrical diode using carbon and tantalum anodes, a Marx charge voltage of 75 kV, and a 12-cm diode AK gap, the 6 MV rated output voltage of Mercury was achieved with a peak current of 285 kA and with 75 kJ delivered to the load by the main pulse. Circuit simulations of the complete MIVA agree with these measurements. PIC simulations showed the cylindrical diode behaving as expected. With tantalum anodes the cylindrical diode produced ~500 Rad (CaF_2) at 1 meter at this Marx charge and AK gap.

VI. REFERENCES

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